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USE OF A CHARGE COUPLED DEVICE (CCD) ARRAY AS A MEDIUM-SPEED STREAK CAMERA

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SEPTEMBER 1992

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A 14-bit scientific Charge Coupled Device (CCD) camera has been used as a medium-speed streak camera through software modifications that preserve the high dynamic range and excellent sensitivity characteristic of these cameras. Line shift speeds as short as 8.1 μs are found to have no detrimental effects on image quality as long as light intensity is kept below saturation levels. Examples of streak images from shock tube studies of reactive systems are presented.

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1. INTRODUCTION

There exist many laboratory studies in the areas of ignition, pulsed plasmas, and chemical kinetics that require the recording of a linear array of data with time resolution on the order of microseconds. Examples are spectra from a rapidly changing system and the propagation of shock waves in shock tubes and pulsed plasma devices. The off-the-shelf choices for instrumentation of such studies are film and electronic streak cameras. The latter are optimized for much faster studies and provide limited spatial resolution and dynamic range. The film systems, while made more useful by recent developments in higher sensitivity film, retain the disadvantages of time for processing, limited useful dynamic range, and chemical handling and waste disposal. Other obvious electronic imaging possibilities such as a high-speed, multiple-output linear array are not yet commercially available as cost effective systems.

Earlier applications of Charge Coupled Device (CCD) cameras have demonstrated faster frame rates either through on-chip storage of smaller images or through binning and modification of the camera controls. In the present study, we have evaluated the application of a CCD array in which only a limited number of rows are illuminated and the rest of the device is used for charge storage. This configuration allows slow, high resolution digitization without any custom components. A major goal for our applications is rapid analysis of data to determine the parameters of the next experiment. Another advantage predicted for this approach is increased useful dynamic range. In imaging of shock data, for example, it is desirable to observe smaller, secondary shocks that are often lost in a film record; the need for dynamic range in spectroscopy is often critical. In addition, the digital records allow rapid interface to computer programs for making measurements from the records using the full image information via least-squares fitting or other techniques. Although not fully explored in the present study, it is anticipated that improved accuracy can be obtained in much less time with better analysis techniques than used previously in our laboratory with film. The digital records also allow for cosmetic operations, such as minimizing noise due to laser speckle or window defects, which can help in visual understanding of processes.

2. DESCRIPTION OF EXPERIMENT

The measurements made in the present study are density gradients due to shock waves and chemical reactions in a 6.2-m-long shock tube. The shock tube is typically driven by helium which is pressurized sufficiently to burst a mylar diaphragm. The subsequent shock wave raises pressure and temperature and

is used to study chemical kinetics and heat transfer. On the side wall near the end of the tube are 20-cm-long windows. A schlieren optical system is set up through these windows to record the gradients during the event. A schematic of the optical layout is shown in Figure 1. The main components are a nominal 5-mW HeNe laser (632.8 nm), a pair of 20-cm-diameter f/6 mirrors, the window-length slit at the windows, and two lenses for beam expansion and imaging onto the detector. A cylindrical lens was used to focus the light from the laser to a line near the focal point of the first mirror in order to fill the mirror and provide parallel light through the region which includes the end of the shock tube. The second mirror re-images the source onto the wire, which blocks all light except when there is a density gradient change in the region between the two mirrors. This arrangement is commonly referred to as *dark-field schlieren photography*. The final lens images the long slit at the shock tube window onto the detector. This lens was changed to vary the magnification—primarily to change the length of the window/slit in the field of view. A 12.5-cm focal length lens gave approximately full coverage.

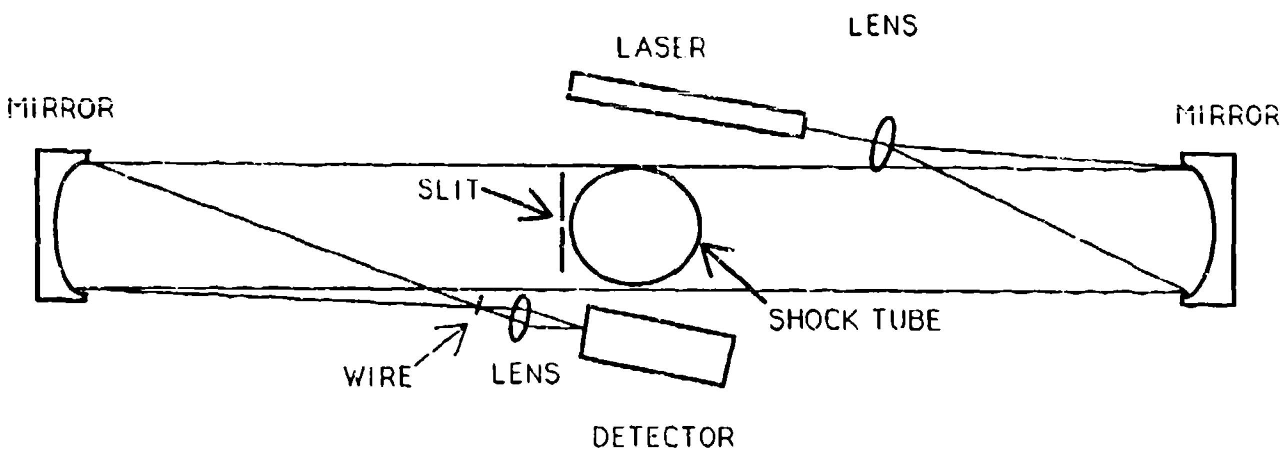


Figure 1. Schematic Diagram of the Optical System Across the End of the Shock.

The detector system is a commercial (Photometrics LTD, Tucson, AZ), thermoelectrically cooled, scientific CCD camera with a Thompson THX31156 sensor. The CCD is a 1,024 x 1,024 array of 19-μm square pixels. For the images shown here, the chip temperature was near -35C. Full well depth on this particular chip was measured at 348 Ke. Signals are digitized with 14-bit accuracy (16,384 counts full scale). The drive software has been modified to allow a parallel register shift every 8.1 μs or slower

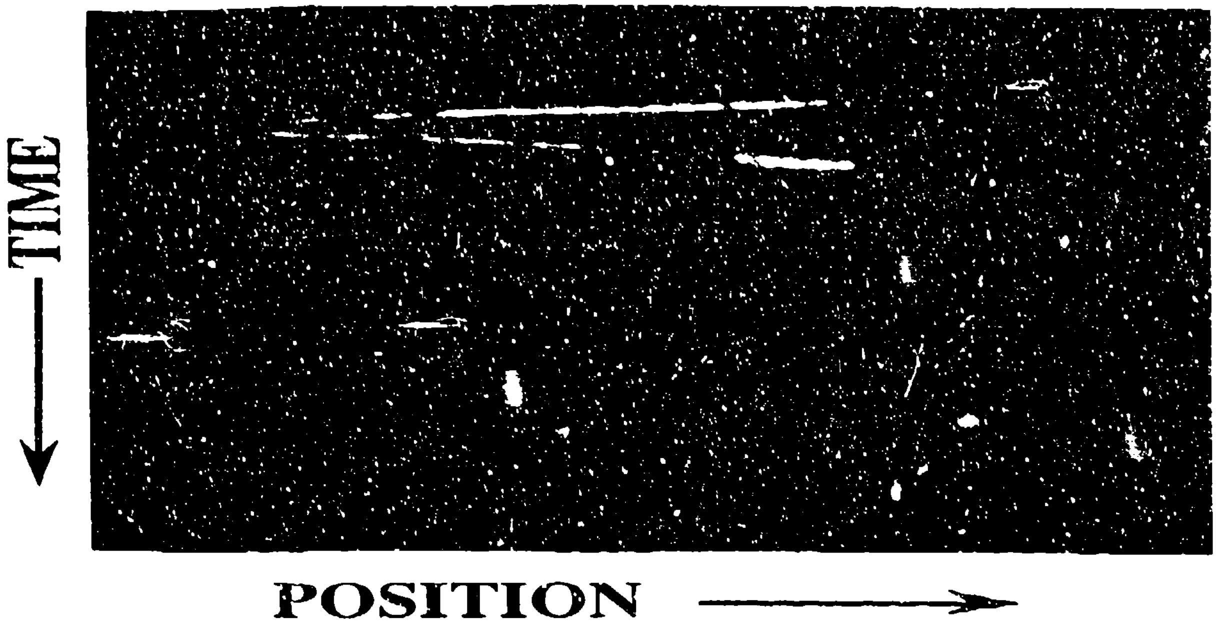
during illumination, starting with an external trigger. In our measurements, the slit near the shock tube window is imaged onto approximately five rows of the chip. No masking was done on the detector.

Since the slit is imaged near the top of the CCD and a relatively slow (5-ms opening) leaf shutter was mounted on the camera, it was necessary to lock open the camera shutter prior to the event. A fast-acting shutter was placed near the laser source where the beam diameter was small and laser illumination was provided only while the CCD was parallel shifting, which avoided saturation and blooming. Because the camera shutter was open for relatively long periods--up to a few seconds—a narrow bandpass dielectric filter was required at the detector entrance to reject ambient light.

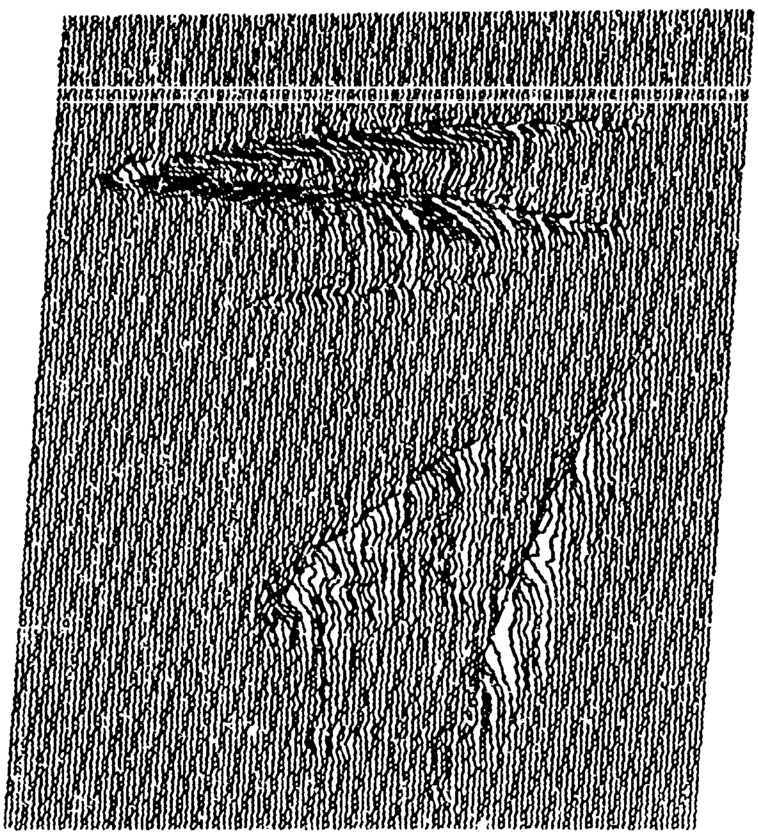
3. OBSERVATIONS

3.1 Open Air Shocks. The first set of experiments was done in a windowless configuration in order to remove any constant schlieren streaks due to window imperfections. The main purpose of this step was to avoid masking possible streaking from charge transfer problems as the camera was operated. A photograph of a typical event record taken from the computer screen is shown in Figure 2a. In this picture, time goes from top to bottom. As with all of the images shown here, the CCD was shifted at its maximum rate, corresponding to 8.1 μs/shift. The incident shock wave enters the field of view from the right and reflects off an object just out of the field of view to the left. Although they are difficult to see in the photograph, the wave bounces back and forth at least one more time. Two later waves are seen which are slower flows of gases out of the tube. Although the image does not convey the full dynamic range of the record, it can be seen that there are no serious image lag or streaking problems due to the rapid charge shift (i.e., we are operating in a comfortable range for the chip). A hidden-line plot of the negative of this image is shown in Figure 2b.

Figure 3 shows the intensity values from a single vertical line near the center of the image (i.e., it gives the signals seen at one position as the waves pass that point). Apparent are the excellent signal to noise, good symmetry of peaks, and the useful dynamic range. The base of the left-hand peak suggests an interference pattern from the laser diffracting through the slit at the window. The other major laser effect is the speckle pattern which causes some of the light and dark variations across the image. The laser speckle pattern does not change appreciably during an image, and can be readily removed or minimized. There are also well-established techniques for eliminating laser speckle from the original image when required.

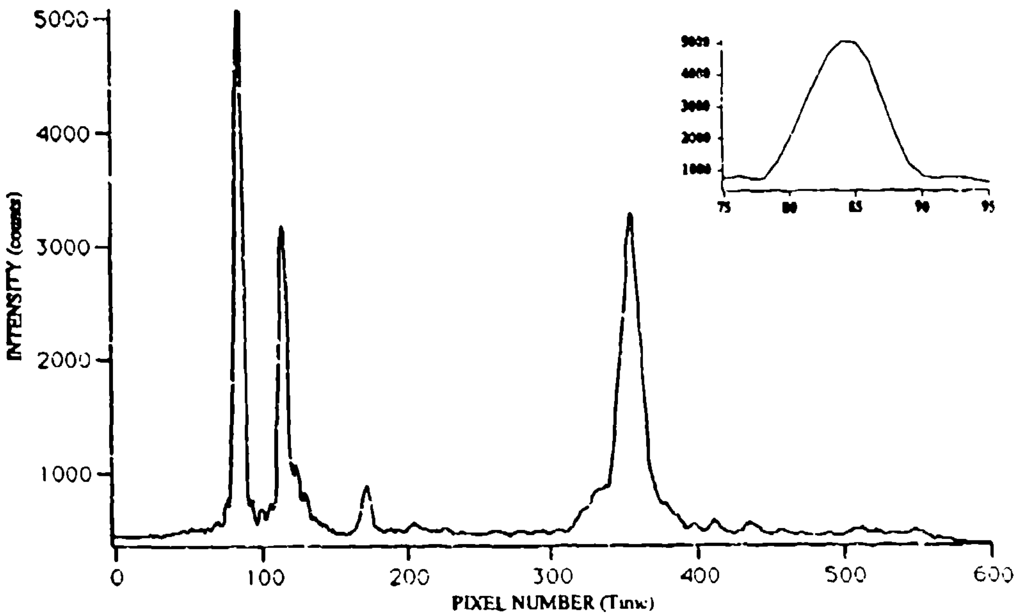


(a)



(b)

Figure 2. (a) Photograph and (b) Hidden-Line Plot of Record of Open Air Shock Wave Propagation. (1,024 x 600 Pixels).



Note: Inset shows an expanded profile of the left-most peak.

Figure 3. Plot of Single Vertical Line Intensity From Figure 2a.

3.2 Short Time-Delay Detonation. Figure 4 shows an event through the windows of the shock tube where a mixture of hydrogen, oxygen, and argon are subjected to incident and reflected shocks which heat the gases past the ignition point. A sharp reaction wave then propagates to the right from an ignition point near the end wall, which is on the left in the image. Later in time other events are seen taking place, including the cooling of the gas by heat transfer to the end wall. Figure 5 shows an intensity plot of the three sharp waves near the middle of the window. Of interest to the person studying these reactions is the relative widths of the waves. The reaction wave is almost as narrow as the incident shock (7 pixels FWHM and 6 pixels FWHM, respectively), indicating the vigorous reaction characteristic of a detonation wave.

3.3 Charge Smear. To this point, the images appear to be easily satisfactory with excellent dynamic range. Problems quickly arose when image intensity was increased in order to fill the dynamic range of the CCD. In Figure 6 is shown the result of having peak signals at a level near 9,000 counts as recorded; since the charge is clearly smeared over many pixels, full charge capacity was probably approached or exceeded at some locations. The degree of smearing is clearly much worse in a few places where the laser

Figure 4. Photograph of Streak Image Record From Incident and Reflected Shocks Through Explosive Mixture and Subsequent Strong Reaction or Detonation. (1,024 x 575 Pixels).

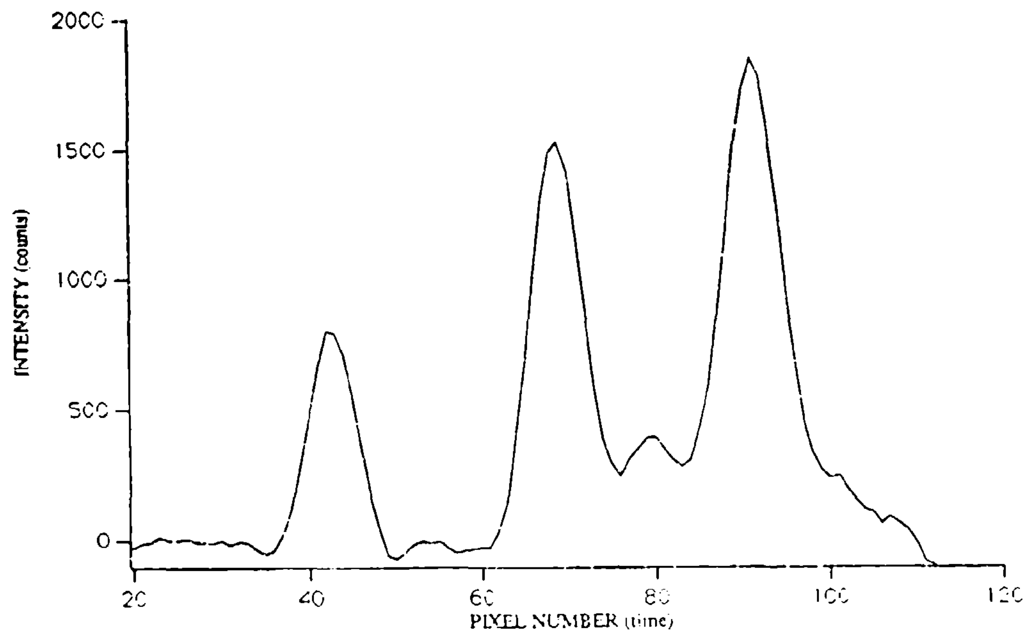


Figure 5. Vertical Line Profiles of Three Main Shocks at Fixed Position Near the Center of Figure 4.

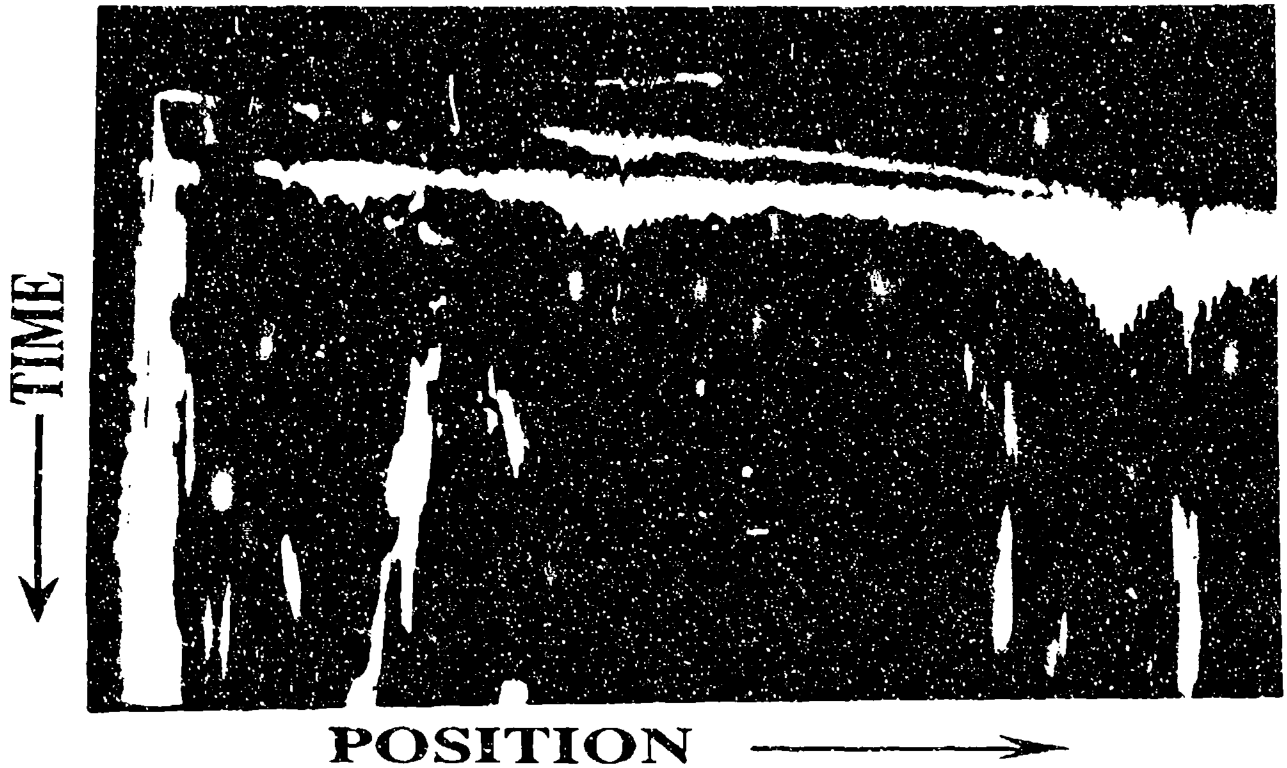


Figure 6. Photograph of Streak Image of Explosive Mixture With Prompt Reaction at Excessive Light Intensity Level. (600 x 500 Pixels).

was brightest. The degradation of wave intensities is shown in Figure 7, which is the intensity plot of a vertical line just to the right of picture center. As can be seen, all three of the lines are asymmetric, although the detonation wave is affected the most. The advantage of digital imaging is that, if necessary, time-of-arrival measurements could be made from even this poor quality data by using the leading edges of the waves.

4. DISCUSSION

The first measurements that are of interest from images such as those above are the linearity and slope of the incident and reflected shocks. From these values and knowledge of the preshock temperature and pressure, thermochemical calculations are performed to obtain the temperature and pressure of the post-shock gases. Note that pressure can be measured readily, and it is used as a check of the conditions. In the other images with detonation waves, the delay time and point of origin of the detonation are the additional values to be measured. All of these parameters are readily obtainable from these images with sufficient accuracy.

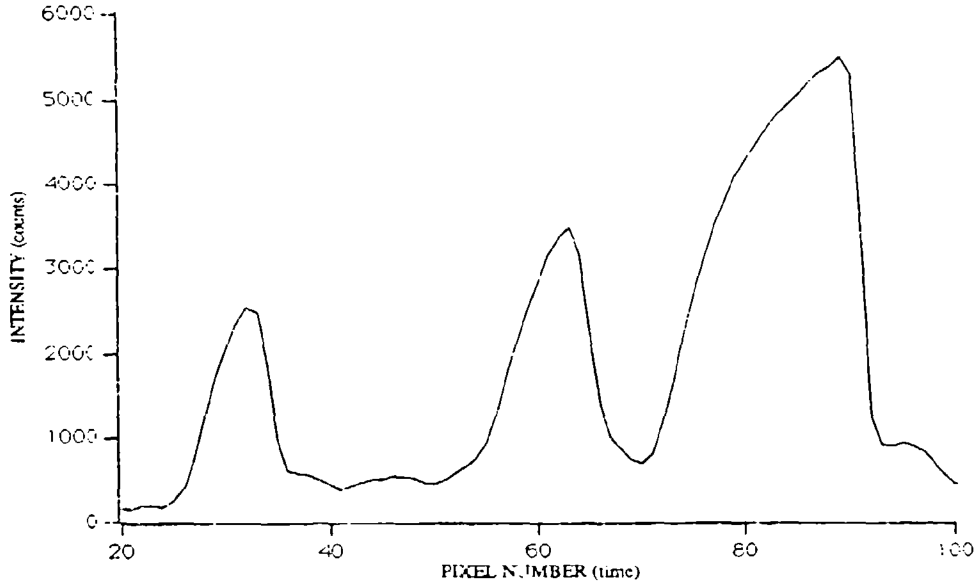


Figure 7. Vertical Line Profile From Near Center of Figure 6 Showing Effect of Charge Smearing on Peak Shapes.

5. FUTURE STUDIES

The second major application of this technique in our laboratory is in the rapid recording of spectra from transient events. These events include both studies of the chemical kinetics behind the shocks imaged above and atomic spectroscopy for temperature mapping in pulsed plasmas. Preliminary studies have been done to demonstrate that imaging the spectra onto a few rows of an unmasked CCD chip is not a major barrier. There are some interference effects of the laser as it passes through the slit at the shock tube windows, as seen in Figure 3; these can be reduced significantly with modest effort. In the case of the plasma, intensity is clearly sufficient. For the chemical kinetics, absorption measurements are required for quantitative measurements. The effect of constant, bright illumination of the chip or possible charge transfer or blooming problems need to be studied in detail. It appears that chemical ignition/combustion reactions may not have sufficient emission intensity for recording in this manner.

For many studies of interest, one would like a 1-μs time resolution. This rate of shift had been our goal at the start of the present study. Preliminary designs of specially fabricated chips that can shift

charge at significantly faster rates, and yet retain cost effectiveness, dynamic range, and large number of pixels, are presently being pursued under contract.

6. CONCLUSION

The application of a scientific grade CCD camera as a medium-speed streak camera has been demonstrated successfully in the imaging of shock phenomena. Dynamic range is excellent. The advantages of rapid visualization and analysis of data are obvious.

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